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FINAL REPORT

EIGHTEEN-INCH DIAMETER EXPULSION DIAPHRAGMS

Jet Propulsion Laboratory
California Institute of Technology
Contract No. 950569

15 September 1966

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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FOREWORD

This report was prepared by the Reaction Control Systems Group of the Aeronautical Division of Honeywell, Incorporated. The work was performed under JPL Contract No. 950569, as a follow-on effort to the first five phases of JPL Contract No. 950569 and a previous JPL Contract, No. 950243. The work has been under the direction of Mr. Howard Stanford of the Jet Propulsion Laboratory, California Institute of Technology.

Special acknowledgement is given to Richard Gillitzer and Donald Tome of the Aero Model Shop for their work in special tool development.

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SECTION 1
INTRODUCTION AND SUMMARY

INTRODUCTION

This report discusses the efforts and results obtained in two basic areas of investigation in all-metal, positive expulsion diaphragm development. These are:

1) Diaphragm recycleability
2) Diaphragm fabrication from stainless steel and titanium.

Diaphragm recycleability efforts consisted of phase VI, a Controlled Motion Mechanism and phase VIA, Diaphragm Hoop Reinforcement. The fabrication of diaphragms from stainless steel and titanium was covered under phase VII. This report treats each of these phases in a separate section, in which background, design, fabrication and tests are described, followed by conclusions, and recommendations.

SUMMARY

Phase VI

Several phase III type * reinforced diaphragms were fabricated for purposes of investigating the merits of a controlled-motion mechanism to prevent tipping of the all metal expulsion diaphragms during operation. It was anticipated that such control would minimize the formation of double folds which invariably led to diaphragm failure. After consideration of a flight-weight

* Refers to diaphragms fabricated in phase III of JPL Contract 950569 with heavy, reinforced "forward" sections and thin "reflected" sections.

design of such a mechanism, a laboratory type of mechanism was fabricated which functioned to completely prevent tipping of the diaphragm in the area of the outer convolution. Tests conducted on the diaphragms utilizing this control mechanism showed that complete elimination of the tendency to tip was not the answer to the problem of double fold formation. Little effect, if any, was noted on the severity or number of the folds. At this point phase VI was terminated pending redirection of effort per phase VIA.

Phase VIA

Redirection of phase VI effort involved the investigation of and the merits of added hoop strength to the reflected portion of the outer convolution. Two configurations to accomplish this investigation were chosen and are illustrated in Figures 9 and 10. Eight such units were successfully chem-milled from a total of ten hemispheres. Tests on the units starting with both the hemispherical and convoluted shapes showed that neither of the hoop reinforcing configurations enhanced performance of the units. In fact, performance was deteriorated due to the tendency for the ribs to concentrate stress in the hemisphere or diaphragm wall adjacent to the ribs and promote fracture. It was also determined that fabricating the units from thick walled hemispheres by chemical milling was undesirable from a standpoint of wall thickness tolerance and surface finish.

Phase VII

Five each of stainless steel and titanium hemispheres were purchased from Aircraft Hydroforming, Incorporated of Gardena, California. The stainless steel units were formed from 0.012 inch thick type 321 SST and the titanium units were formed from 0.016 inch thick commercially pure titanium and subsequently chemically milled down to 0.005 to 0.008 inch. All units were eighteen inches in diameter. After a minor modification and addition to the existing telescopic punch and die, efforts to convolute both the stainless steel and titanium hemispheres were successful.

SECTION 2
PHASE VI

BACKGROUND

Experience gained from earlier phases of contract JPL 950569 revealed that the major problem in developing an all metal expulsion diaphragm for multiple or single expulsion cycles was the formation of double folds which caused stresses beyond the capability of the diaphragm material resulting in pinholes and/or cracks. Since it was impossible to set up mathematical equations or other systematic relationships representing the behavior of the folding process, the only data available on the phenomenon is in the form of photographs taken during the actual operation of diaphragms under test. Figure 1 is an example of this data. Note the degree to which the unit is tipped to one side and the double folds occurring in the outer convolution. It seems reasonable that the cause for such tipping lies in a finite difference of membrane thickness or hardness from one point on the unit to another. After several such observations a correlation seemed to exist between the amount of tipping and the number and severity of the double folds which occurred. On the basis of this correlation, Honeywell proposed to investigate the feasibility of providing a mechanical means of preventing this tipping from occurring in the outer convolution of the diaphragm where the problem was the greatest. It was expected that such control would at least reduce the number and severity of the three-cornered folds. This effort was funded under Modification 1 of contract No. JPL 950569.

HONEYWELL'S APPROACH, DESIGN AND FABRICATION

Honeywell's approach to the problem of tipping and double folds began with the two concepts shown in Figures 2A and 2B. These concepts were presented to JPL in Honeywell Proposal Document 4-PH-694. The intent of presenting

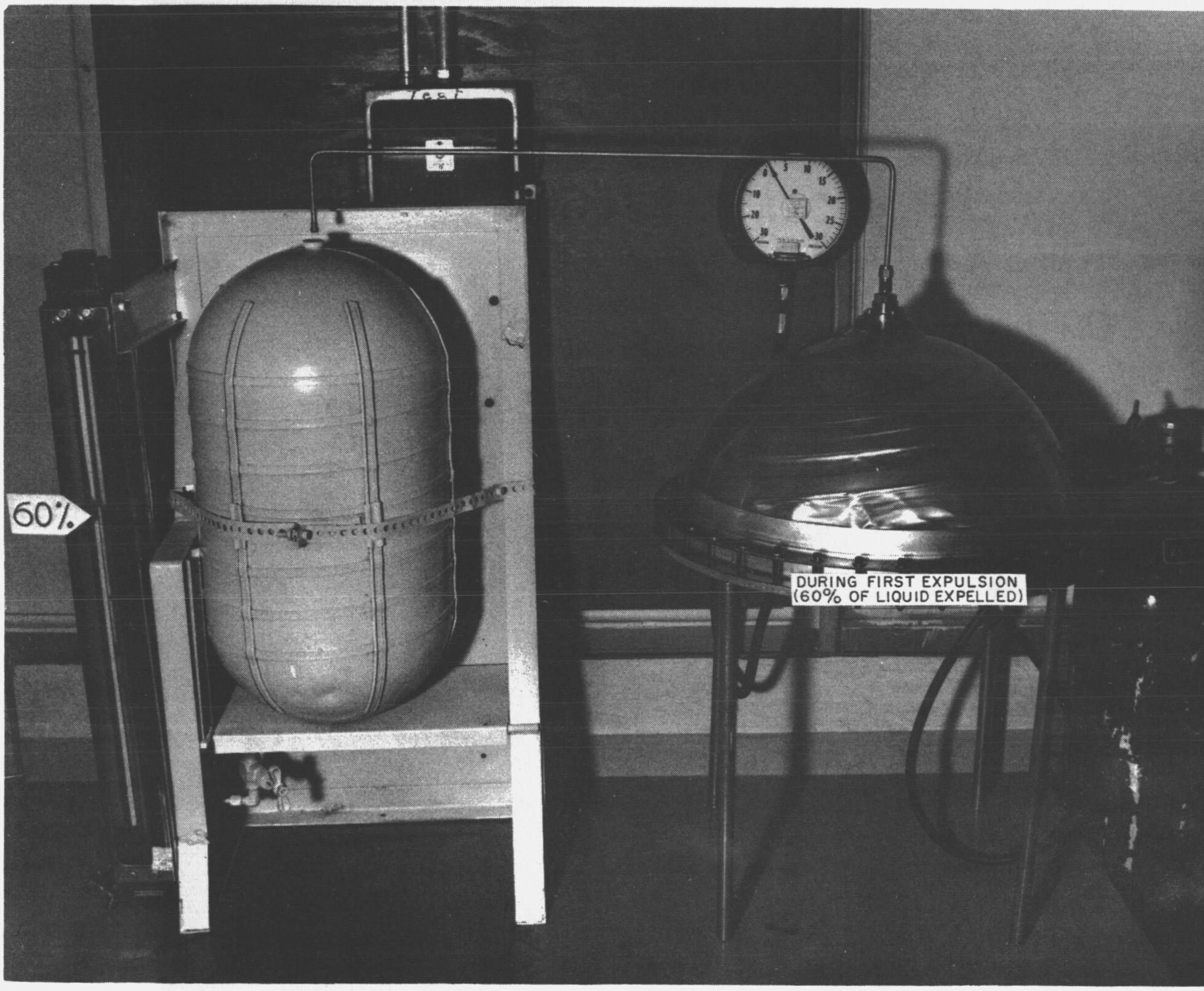


Figure 1. Typical Reinforced Diaphragm Performance
Without Controlled-Motion Mechanism

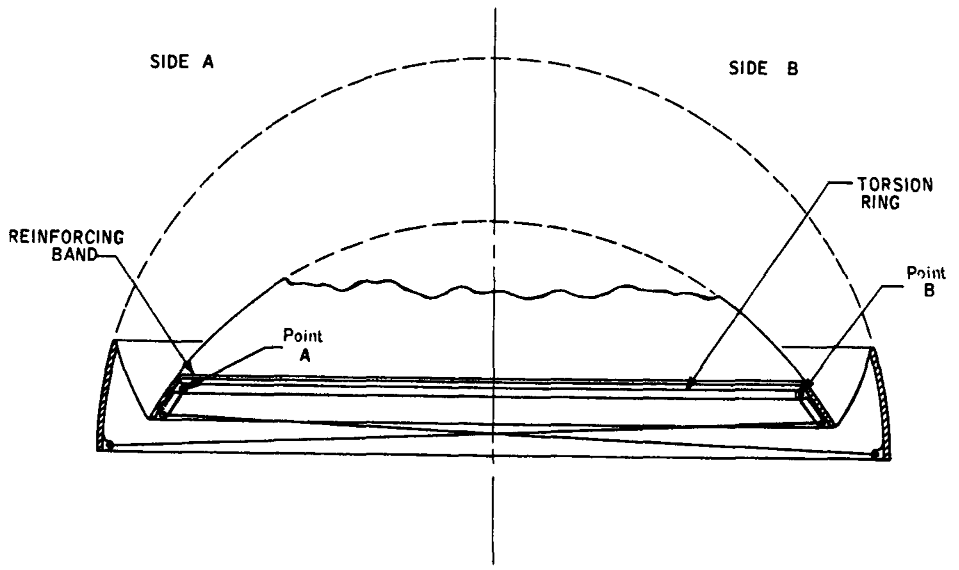


Figure 2a. Torsion Ring Feedback Concept -- Diaphragm Controlled Motion Mechanism

In the torsion ring feedback concept, a torque results in the torsion ring as the diaphragm rises. If, for instance, side A would tend to rise at a faster rate than side B, tension in the wire attached to the lever pivoting about point A would be greater than tension in its opposite (B) counterpart. The result would be: 1) Greater downward component of force on side A, and 2) Counterclockwise couple at point A, tending to elevate point B, thus equalizing the two sides. The device also tends to resist anv tendencv of the diaphragm to shift off center.

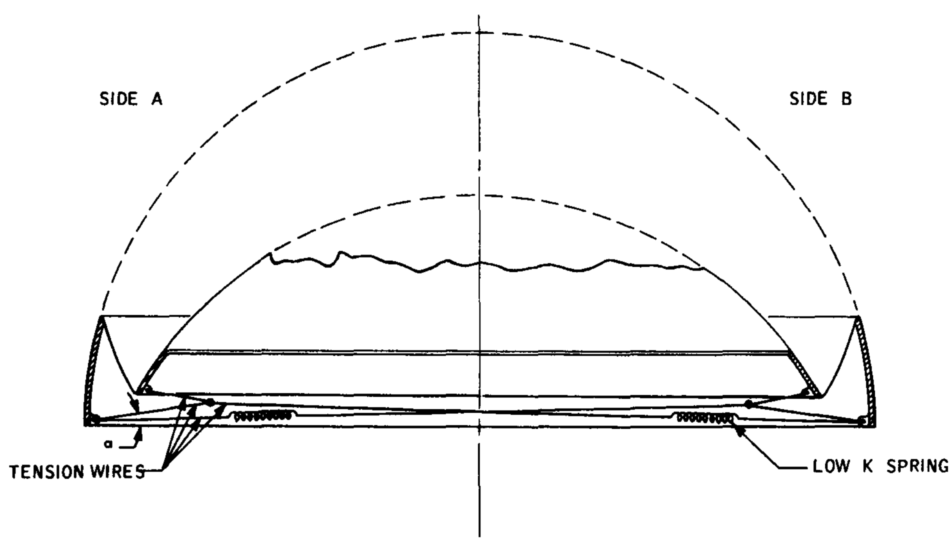


Figure 2b. Spring-Wire Concept -- Diaphragm Controlled Motion Mechanism

In the tension wire concept, the angle α increases as the diaphragm rises. The downward restoring force increases proportionately. If, for example, side B would tend to rise at a faster rate that side A, the downward restoring force on side B would increase while side A equalizes.

these concepts was not to illustrate definite hardware but rather to show, in general, the type of control that would be considered for flightweight type of hardware. The idea here was to design a mechanism that would provide counter forces to the forces which tend to make the diaphragm tip during operation. In operation, the mechanism would function as follows: As one side progresses faster than the opposite side, the mechanism would provide a greater force on the "fast side" tending to slow it up or stop it until the "slow side" would catch up. Note the explanations accompanying the figures.

After several considerations, in addition to the two concepts shown, it became apparent that a flightweight mechanism which would meet all the requirements of weight, space and performance would indeed be more complex than at first anticipated.

Figure 3 is a brief graphic analysis of the forces and force gains involved in using the Torsion Ring Concept (Figure 2A). All A - B lines represent a lever attached to the torsion ring at point A. Point A is the center line of the torsion ring. A wire attaches point B to anchor point C. As point A moves up the dashed line (A_1, A_2, A_3 etc.) it can be seen that the lever, line A - B, rotates, torquing the torsion ring about point A. This torque results in a force or tension in the wire attached to the anchor C. It is the downward component of this tension in the wire which provides the desired leveling force when the diaphragm tends to tip. θ_1 is the angular displacement of the torsion ring as the ring moves upward from A_2 to A_3. θ_2 is the angular displacement of the ring as the ring moves from A_4 to A_5. The distance between A_2 and A_3 is equal to the distance between A_4 and A_5 but θ_2 is much greater than θ_1. Since θ determines the magnitude of the torque and, hence the leveling force, it can be said that the force gain, $\frac{dF}{dS}$ is greater as the diaphragm approaches the fully extended position than at positions near or at the collapsed position where $\frac{dF}{dS} \to 0$. This is just the opposite of what is desired.

At this point, rather than to invest time and funds in developing a more complex flightweight mechanism (assuming it could be done) it was decided that a laboratory

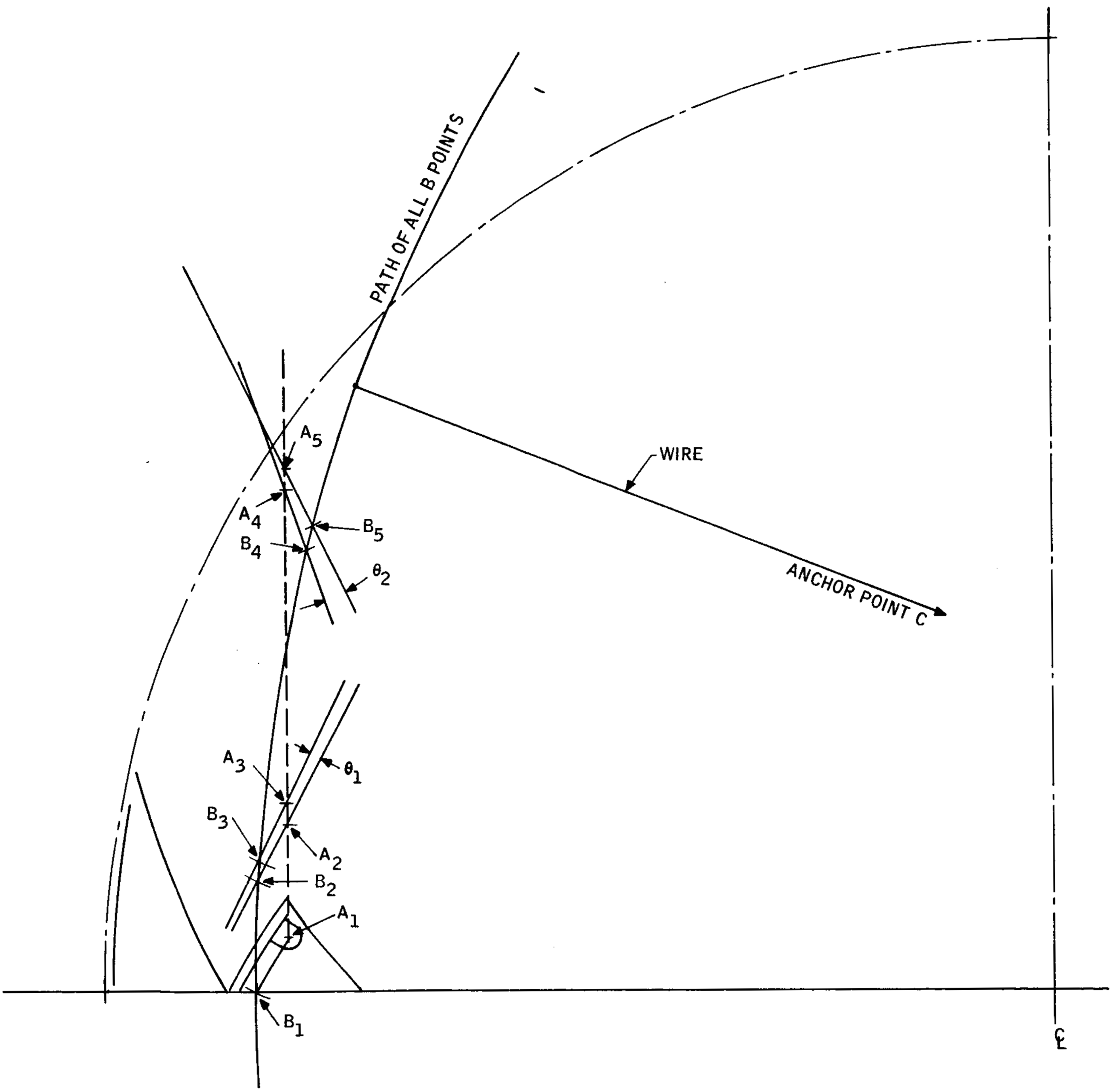
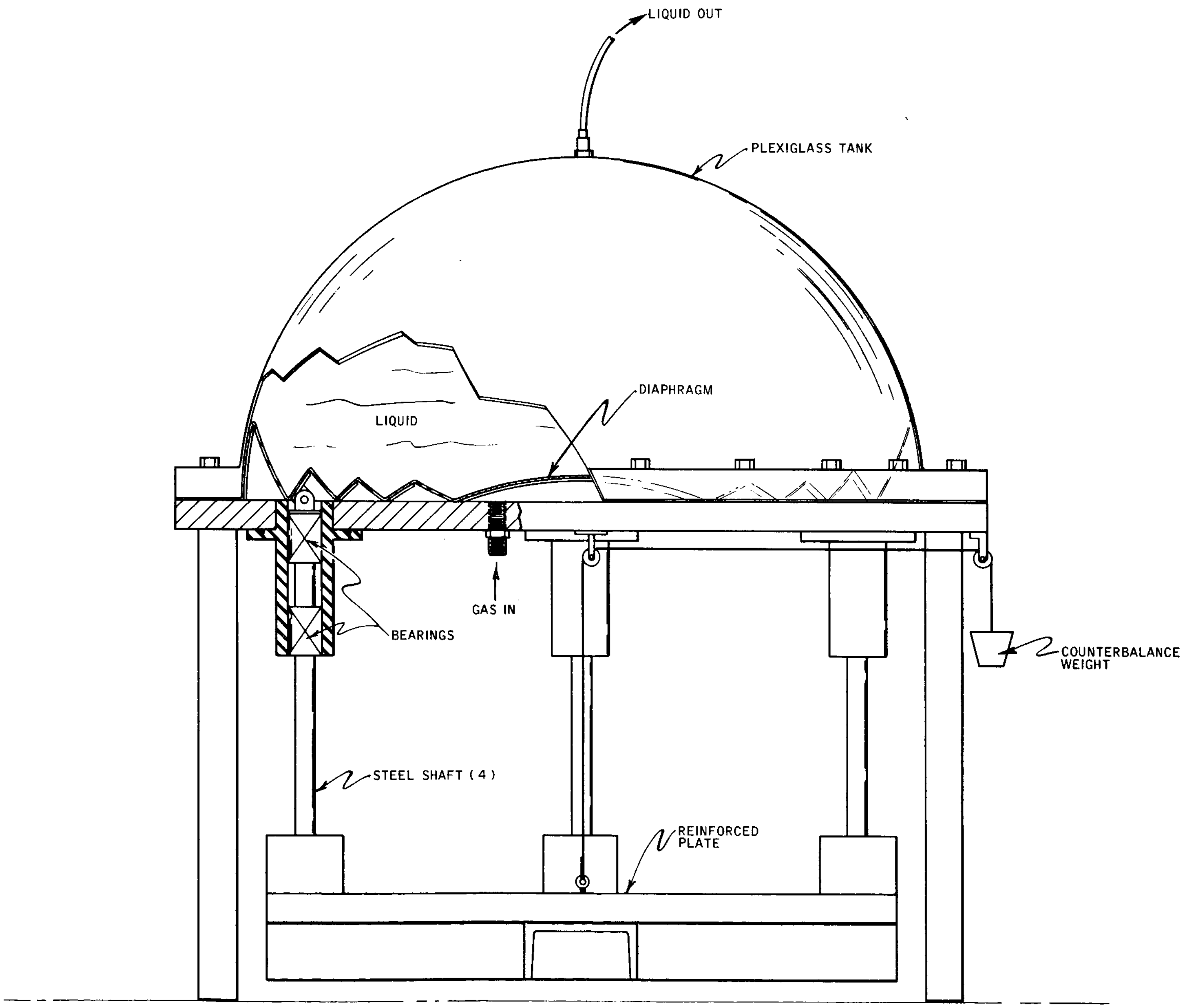


Figure 3. Graphic Analysis -- Torsion Ring Concept



NOTE: TIPPING OF DIAPHRAGM IS PREVENTED BY FORCED SYNCHRONIZATION AT FOUR POINTS, VIA THE STEEL SHAFTS RIDGIDLY CONNECTED TO THE REINFORCED PLATE.

Figure 4. Laboratory Model -- Controlled Motion Mechanism

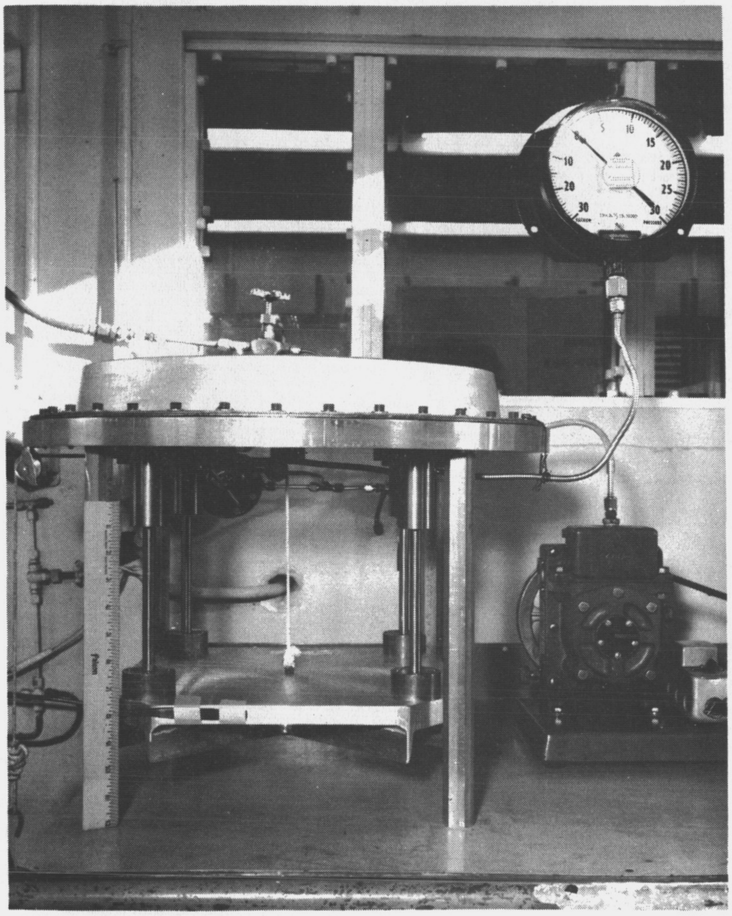


Figure 5. Diaphragm Readied for Test with Controlled Motion Mechanism

Figure 6. Diaphragm at end of Test-- Without Lucite Dome

type of mechanism should be fabricated which would provide the maximum control obtainable to prevent tipping of the unit without regard to weight or space. The rationale behind this decision was that for a minimum of expense it would be possible to determine the value of a motion-control mechanism and, if the results were good enough further efforts towards developing flightweight hardware would be pursued. Figure 4 illustrates the laboratory type mechanism which was built. Four heavy, hardened steel rods, running in bearings and fastened to a rigid plate, were pinned to one of the heavy reinforcing rings as shown. As is evident, as one side of the diaphragm would tend to progress faster than the opposite or adjacent sides, forces would be transmitted through the mechanism and prevent any differential motion from one point to another. Weights were provided which, through a cord and pulleys, balanced out the weight of the heavy plate and rods. The mechanism performed exactly as desired.

TESTS AND RESULTS

Five phase III type reinforced diaphragms were fabricated. Figure 5 shows one of these diaphragms mounted in place on the mechanism ready for test. For this test the lucite dome was not used, however this proved unsatisfactory since without the restraining force of the dome at the top of the outer convolution, the test diaphragm became out-of-round which was cause for termination of the test. Figure 6 shows the results of this test. A total of five tests were conducted using the controlled-motion mechanism and lucite dome. The first two of these tests were conducted using diaphragms which were quite badly wrinkled in the outer convolution during fabrication. These two units did not yield any useful data other than to prove satisfactory operation of the control mechanism.

A few wrinkles were present in the outer convolution of the third unit; however, most of the section was smooth. During the third unit's first expulsion the outer convolution sections which were smooth performed very well. Rolling of the metal was uniform and no traveling folds appeared in these areas. Traveling folds appeared immediately in the wrinkled areas. Since the wrinkles were oriented across the convolution, rather than around it, each acted as a column, resisting the desired rolling action. At the end of the expulsion half-cycle, the wrinkle-free areas were still very smooth. The wrinkled areas showed heavy creasing resulting from the traveling folds.

The unit was then retracted by forcing the expelled liquid back into the lucite tank. Severe buckling occurred immediately in the smooth sections, with minor buckling occurring in the wrinkled or creased sections. It appeared that the sections which had fully expanded to a smooth contour had developed a high column strength which prompted random buckling under the pressure load. The section was held level by the control mechanism during retraction, just as it was during expulsion.

The fourth and fifth diaphragms were very smooth in the area of the outer convolution. Both units were ideal test parts. The results obtained in testing these last two units were not encouraging, however. Figures 7 and 8 show units 4 and 5, respectively, toward the end of the first expulsion cycle for each unit. Note wrinkling due to double folds and traveling creases.

At this point phase VI was terminated pending re-direction of effort.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the described tests and results, it was concluded that preventing tipping of the diaphragm during operation does not significantly reduce the severity and number of wrinkles and that this control, by itself, is not sufficient to pursue further. At this point, however, it was recommended that the idea of motion control be incorporated with an effort to increase the hoop strength of the outer convolution with the thought that the combination of the two might be the answer to the buckling problem. This recommendation was presented in the form of a proposal for a phase VI change in scope. This proposal (Honeywell Proposal Document 5-PH-513) was submitted to JPL in April of 1965.

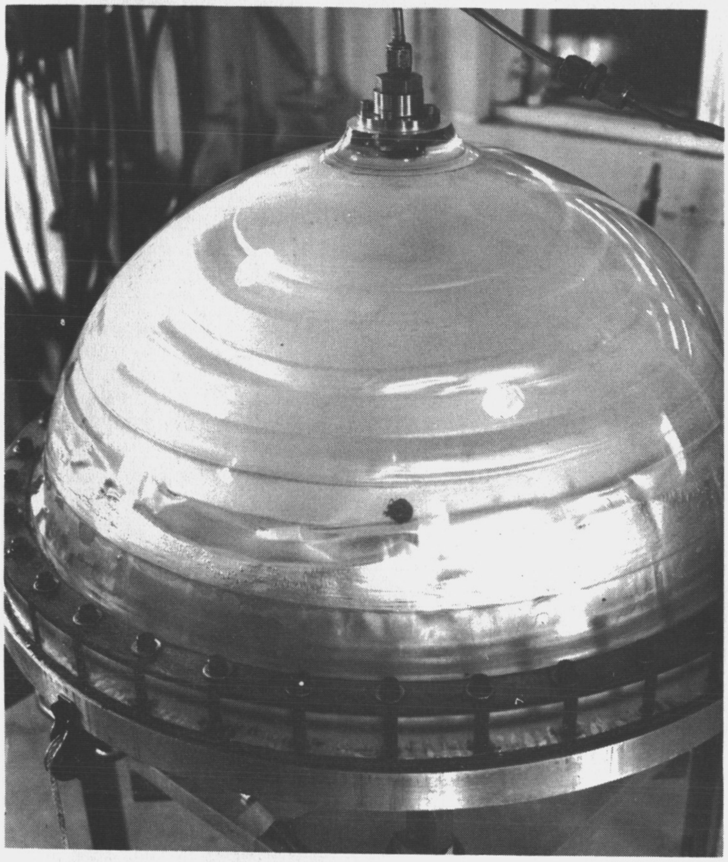


Figure 7. Unit No. 4 -- Test with Controlled Motion Mechanism

Figure 8. Unit No. 5 -- Test with Controlled Motion Mechanism

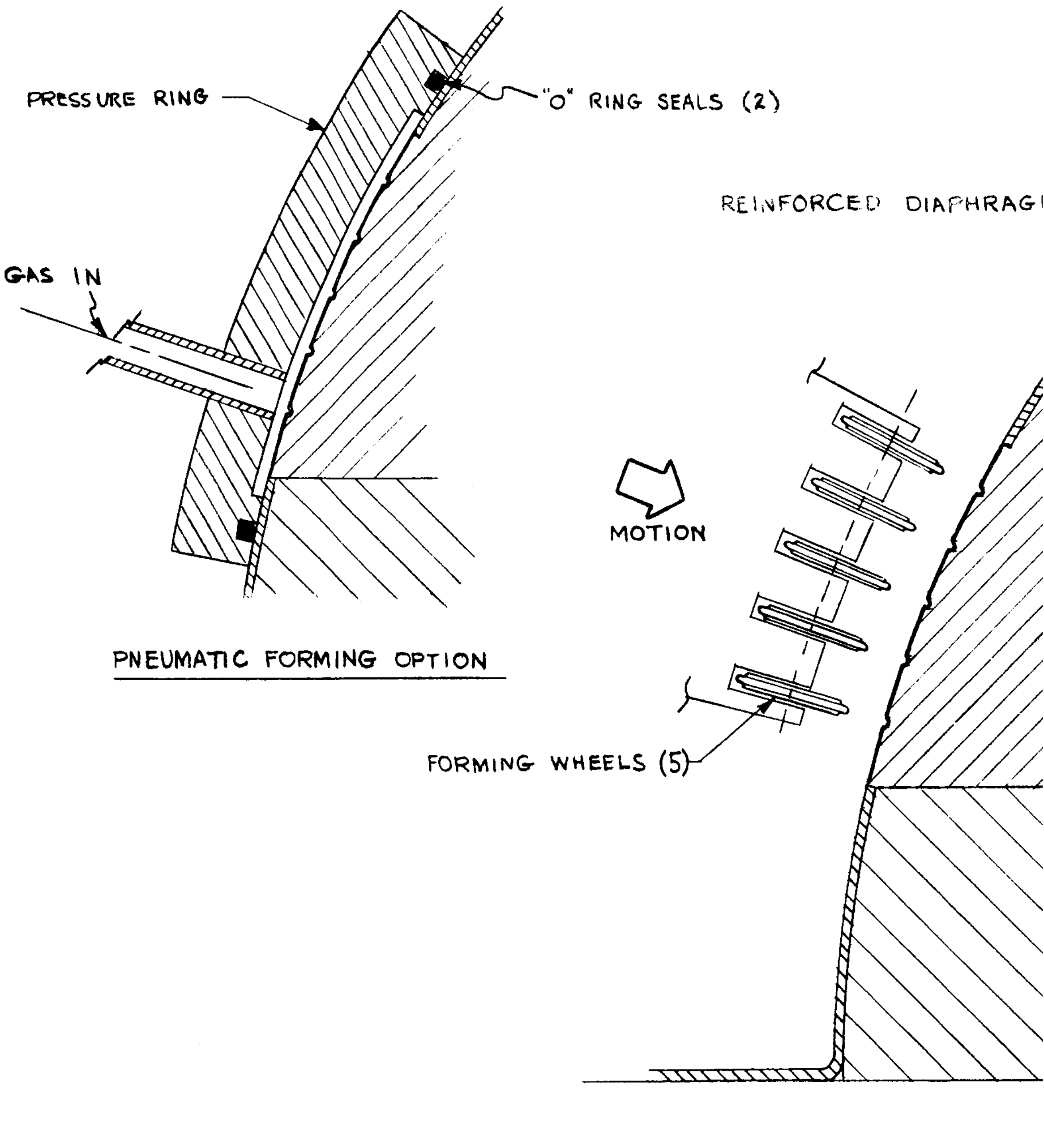
SECTION 3
PHASE VIA

BACKGROUND

Upon termination of phase VI effort and the submittal of Honeywell Proposal 5-PH-513, JPL agreed to a redirection of effort for phase VI by instituting Modification 2 of Contract No. JPL 950569. This redirection of effort consisted of increasing the hoop strength of the outer convolution without appreciably affecting the flexibility of the metal necessary to folding in the desired manner. The increased hoop strength appeared desirable from the standpoint of resisting the formation of double folds.

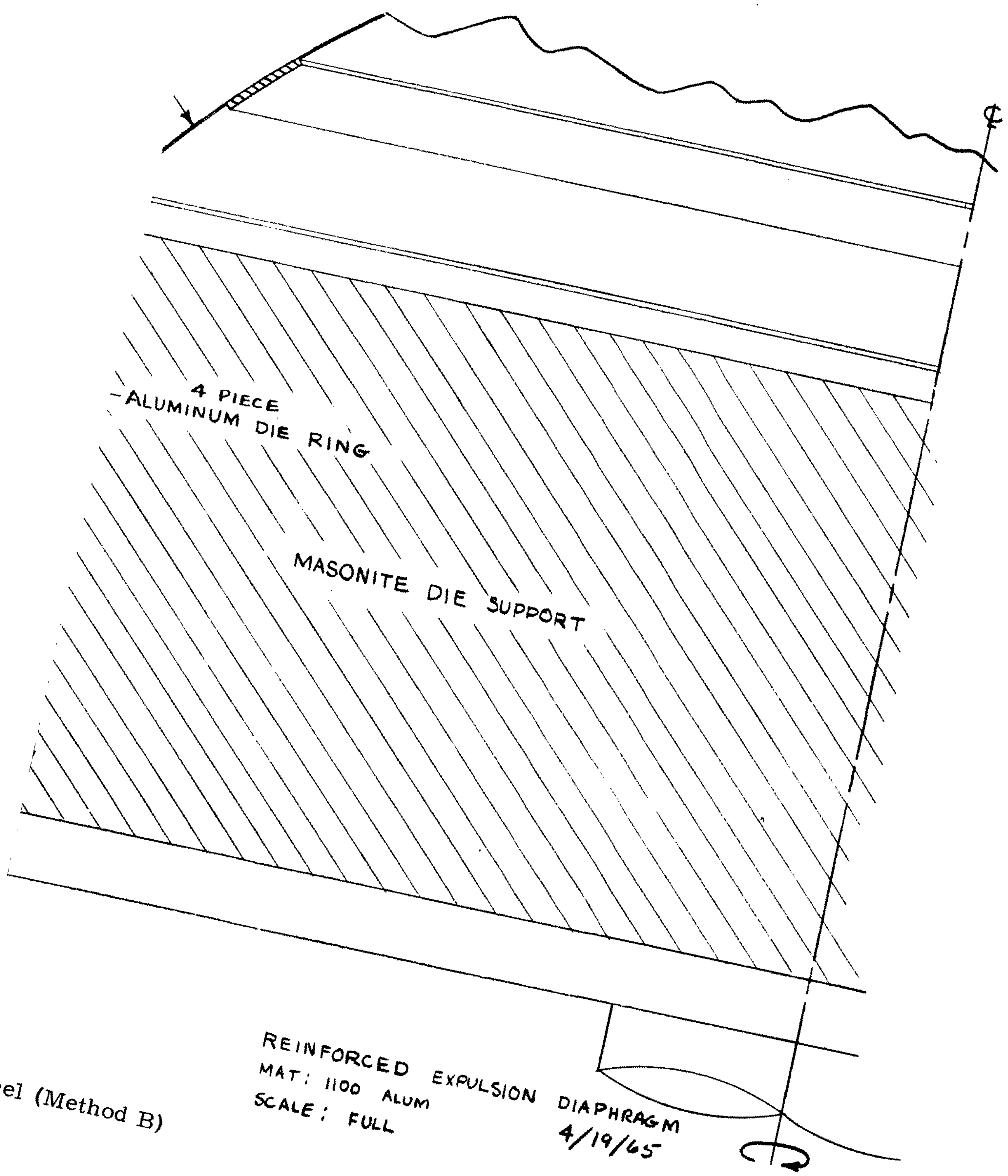
HONEYWELL'S APPROACH

Honeywell considered two basic approaches to obtain the desired hoop reinforcement. Figures 9 and 10 illustrate these approaches. Figure 9 shows two methods of forming reinforced hoops in the metal by forcing it into grooves which are machined into a back-up die. One method uses a wheel or group of wheels to form the metal while the other method used hydraulic pressure to force the metal into the die. Figure 10 shows a cross section of a hemisphere which contains ribs formed entirely by chemical milling. Honeywell's approach was to try both the mechanical forming method and the chemical milling method then to choose the best approach for continuing work.



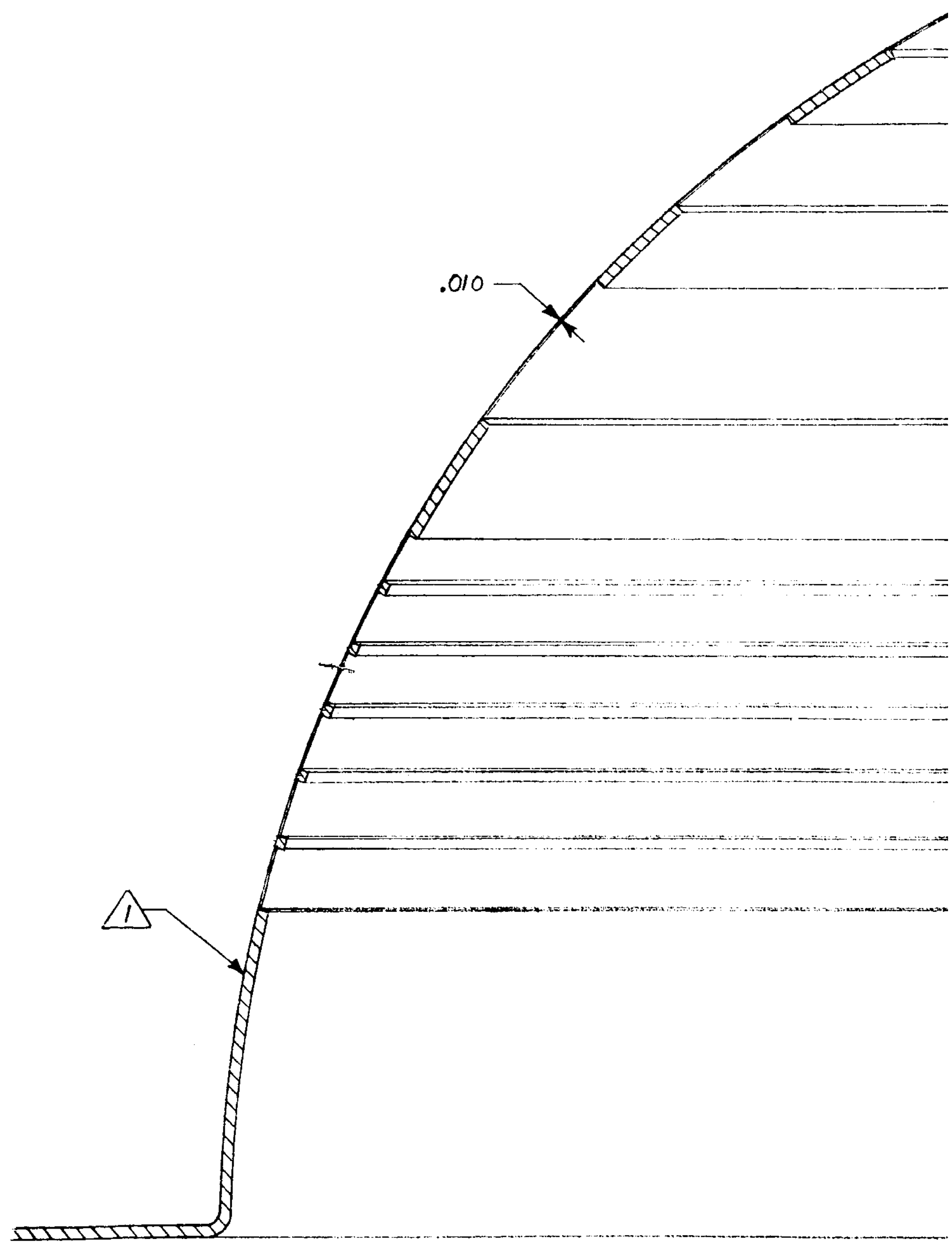
20-1

Figure 9. Rol



Vheel (Method B)

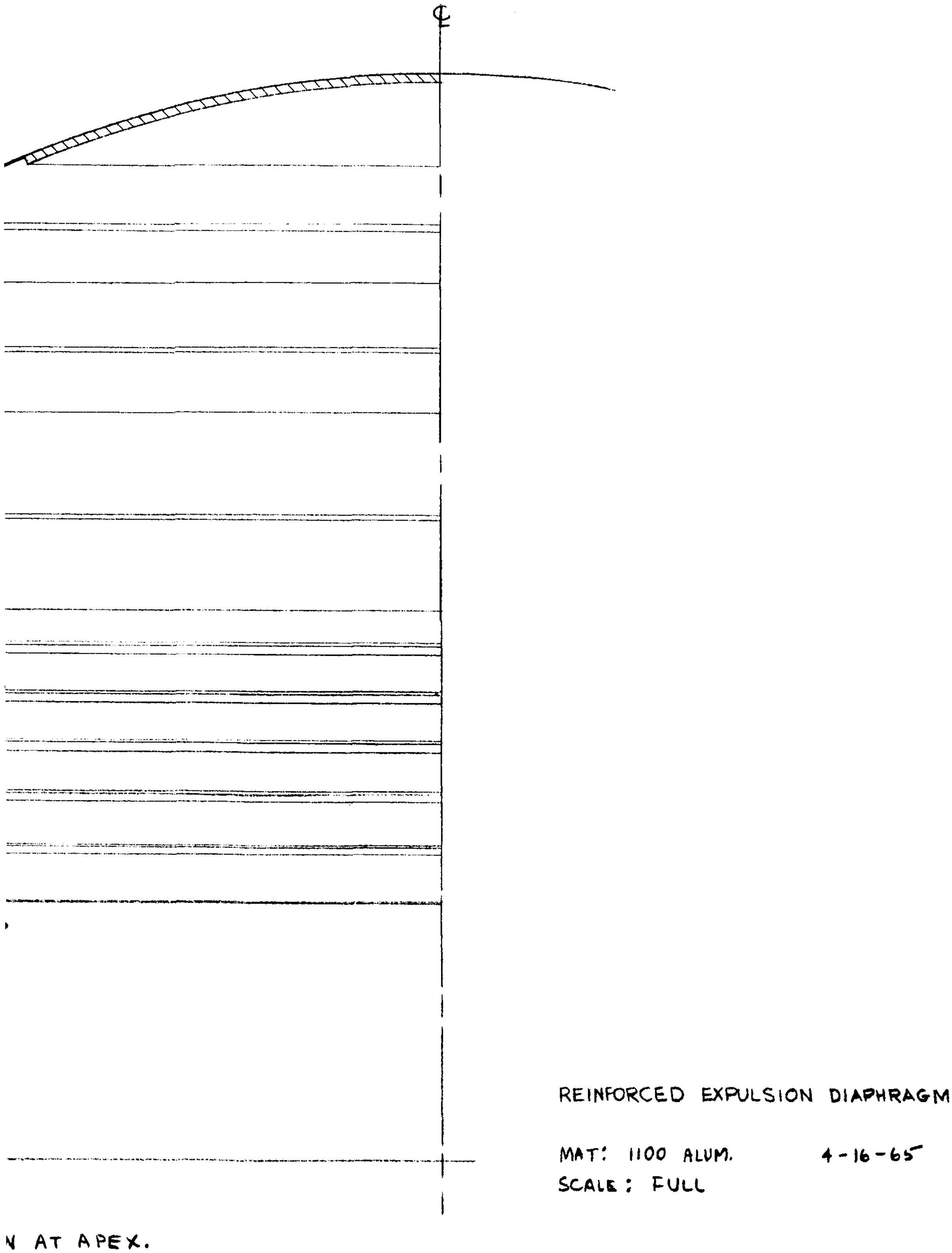
20-2



1 THICKNESS OF REINFORCING MEMBERS .060 MAX NEAR FLANGE TO .0

21-1

Figure 10. Reinfo



21-2

Expulsion Diaphragm

FABRICATION

As can be seen from Figures 9 and 10 both methods require a heavy-wall aluminum hemisphere. A wall thickness of between 0.10 and 0.12 inch was chosen since this was the desired thickness of the wide reinforcing bands. Drawing a hemisphere this thick was determined to be beyond the capability of the air-draw die developed under a previous contract. Rather than increase this capability by reworking the die, it was decided to obtain quotes from various hydroforming companies. Jones Metal Company of West Lafayette, Ohio was chosen to supply ten hemispheres. All hemispheres received from Jones were smooth and free of wrinkles. Despite the thickness of the metal, (1/8 inch nominal sheet stock), the radius between the dome and flange of each hemisphere was maintained at the 0.125 inch maximum requested. According to Jones Metal, a press operation subsequent to the hydroform process was necessary to achieve the small radius. The wall thickness of all hemispheres varied from a minimum of 0.101 inch to 0.118 inch maximum. The thinnest section of each hemisphere consisted of a band located from two to three inches above the flange. Further measurements showed that the wall thickness was very constant about the circumference of any plan parallel to the plane of the flange.

Prior to this time, Hiawatha Metalcraft had proven their ability to perform the necessary chemical milling operation. This they accomplish by first spraying the entire inner surface of each hemisphere with a neoprene liquid rubber masking material. After spraying, the units are baked at 300°F for one-half hour. The material is then stripped from the areas to be milled. A 0.030-inch thick scrap hemisphere, coated with the masking material, is placed over the unit to be milled so that the outside surface of the working part need not be masked. This allows periodic thickness measurements to be easily made during milling.

Figure 11 shows the masking material being removed from an experimental part after the part had been chemically milled to a depth of 0.020 inch.

Figure 11. Removal of Masking Material

Of the ten hemispheres available, the first unit was ruined by a mistake in dimensioning. The next three units were milled to provide the wide bands only, and were further processed by Honeywell to obtain the narrow reinforcing grooves in the outer convolution by the wheel method. Figure 12 shows the retractable backup die and wheel necessary for this operation. As the hemisphere is turned the wheel is advanced against the part, forcing the metal into the die groove. Figure 13 is a view of the inside of one of these units while still in the hemispherical shape. The grooves were all approximately 0.040 wide (width of wheel) and 0.030, 0.035 and 0.040 inch deep in units 2, 3 and 4 respectively. The next four units were chemically milled to provide both the wide bands and the narrow reinforcing ribs in outer convolution (Figure 10). The first of these units was ruined during chemical milling as the metal was milled completely through in one area. Two possible causes for this are either a small thinned section which resulted during forming of the hemisphere or a faster rate of milling in that particular area. The three units which milled satisfactorily were final-machined in the Aero Model Shop to reduce the width and height of the narrow ribs and also to reduce the fillet radius at the base of each rib. Figure 14 illustrates this operation. It was felt that the ribs and fillets were too large and stiff to allow the unit to roll satisfactorily. Figure 15 shows a cross section of one of these units taken after the unit had failed to convolute. This final machining operation was difficult and not completely satisfactory since the hemispheres were not perfectly spherical nor were the ribs perfectly parallel to the flange. An attempt was then made to convolute these three units. This was done after convoluting the stainless steel and titanium units in phase VII since the telescopic punch had to be reduced in diameter to fit the thick aluminum units. One unit convoluted satisfactorily but the other two buckled and fractured in the reflected portion of the outer convolution containing the narrow ribs. It was apparent that this ribbed section was plagued by a number of stress-concentration points caused by the ribs and varying degrees of thickness gradations. It was also apparent at this point that the chemical milling process was pushed beyond its capability in attempting to fabricate these parts. Insufficient control of the process was evidenced when milling the narrow ribs and small fillet radii. starting with a hemisphere having a wall thickness greater than 0.10 inch and reducing to approximately 0.015 in. dimension. Another undesirable feature of

Figure 12. Diaphragm Grooving Tooling

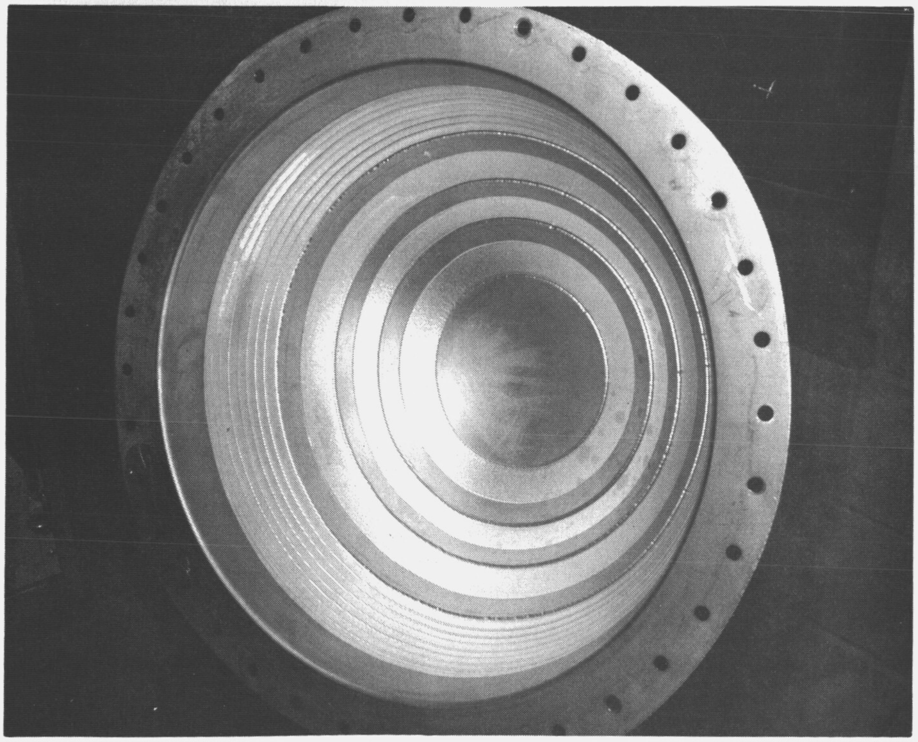


Figure 13. Inside View -- Diaphragm Fabricated by Rolling Wheel Method

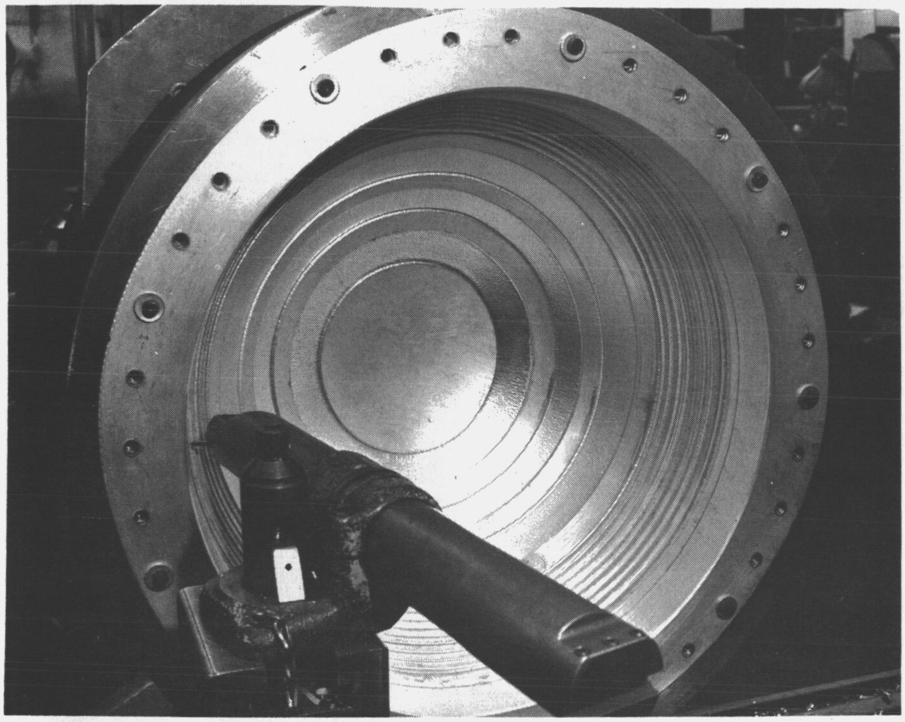


Figure 14. Final Machining of Chemically-Milled Hemisphere

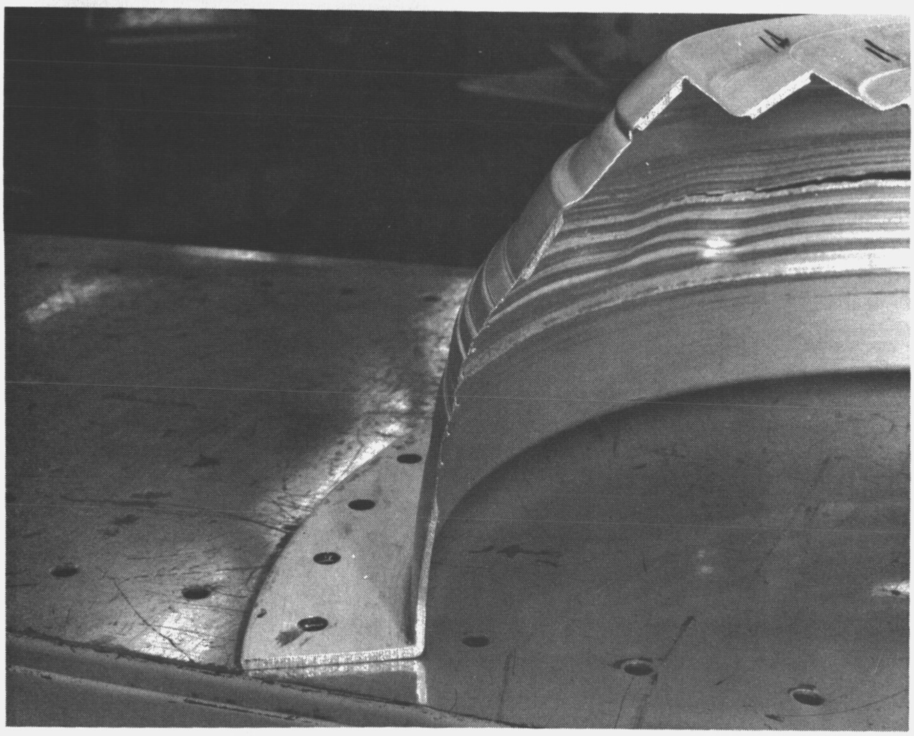


Figure 15. Cross Section of Chemically Milled Hemisphere after Convoluting Attempt

milling to this extent was the rough surface finish obtained as evidenced by Figure 14. Although not measured, the degree of roughness was estimated at from 0.002 to 0.004 inch from peak to valley. The remaining two of the ten hemispheres were chemically milled to provide the wide reinforcing bands as were units 2 through 4. After rolling the ribs into the outer convolution, both units were convoluted but without success. See Figures 16 and 17. Both units buckled and fractured along one of the grooves. This was surprising since the grooves in these two units were only 0.015 deep and little or no thinning was caused by the wheel. Careful observation showed, however that the metal had been etched extremely thin in these areas again evidencing the lack of thickness control when chemical milling from 0.10 inch down to 0.015 inch. Another, and perhaps the most significant contributor to the thickness gradation is the tolerance in thickness of the hemisphere prior to any chemical milling. Even the thickness tolerance of the original sheet stock is significant when considering that the finished part is only 0.015 inch thick. Prior to fabrication, it was estimated that the tolerance on the hemisphere would be ±0.008 in. A tolerance on the minus side of greater than 0.015 inch was observed, however.

TESTS AND RESULTS

Of the ten original aluminum hemispheres purchased from Jones Metal Company, only three units were successfully fabricated and tested. These units were No.'s 2, 4 and 8. Units 2 and 4 were chemically milled to provide the wide reinforcing band in the "forward" sections and further processed in the Honeywell Aero Model Shop to obtain the hoop reinforcing ribs in the reflected portion of the outer convolution. See Figure 9. Unit No. 8 was chemically milled to provide all bands and ribs. See Figure 10.

Figures 18A and 18B illustrate schematically the test setups used. Figure 19 shows four steps in the sequence of testing unit no. 2. Figure 19A shows the unit readied for test with no pressure applied. Figure 19B shows initial deformation at a ΔP across the hemisphere of 12 psi. Figure 19C shows continued

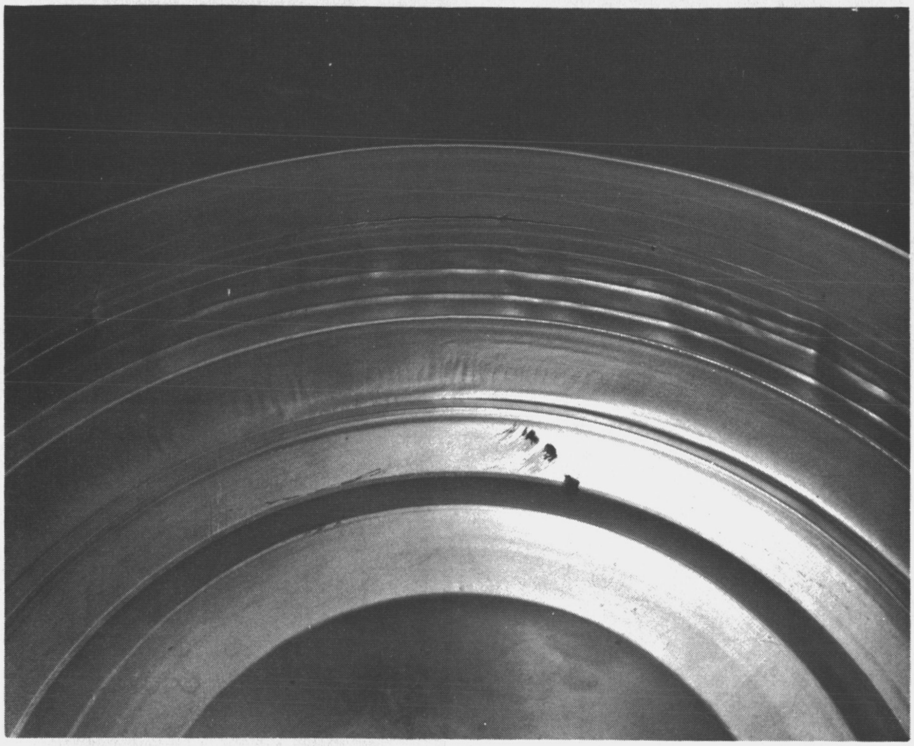


Figure 16. Convoluting Attempt -- Unit No. 9

Figure 17. Convoluting Attempt -- Unit No. 10

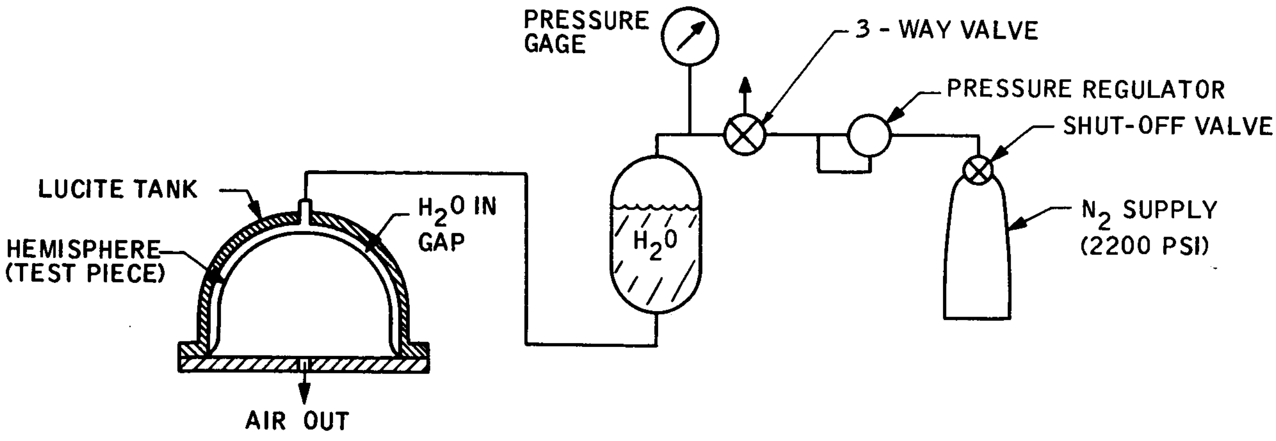


Figure 18A. Test Setup for Hemisphere (Units 2 and 4)

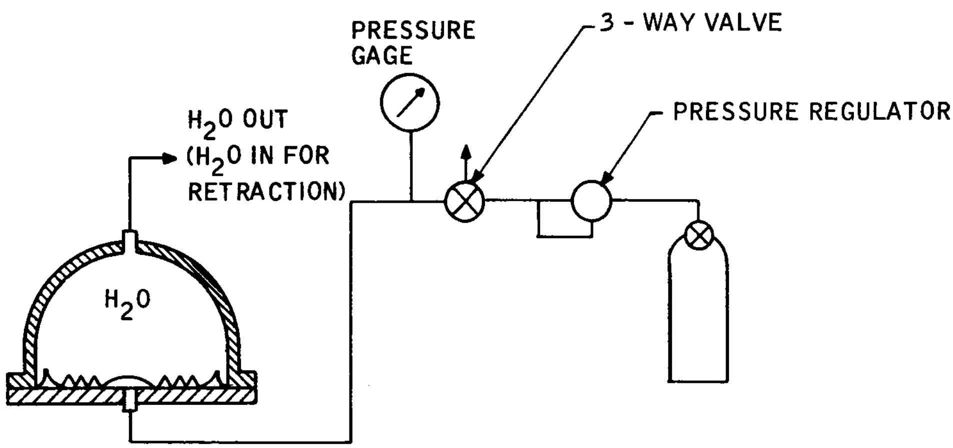
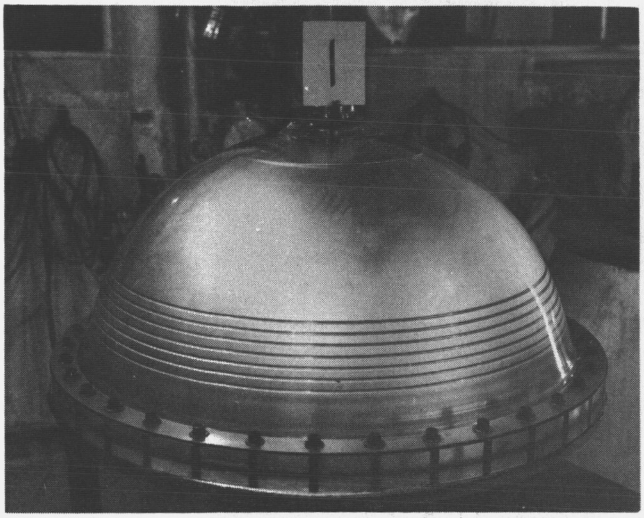
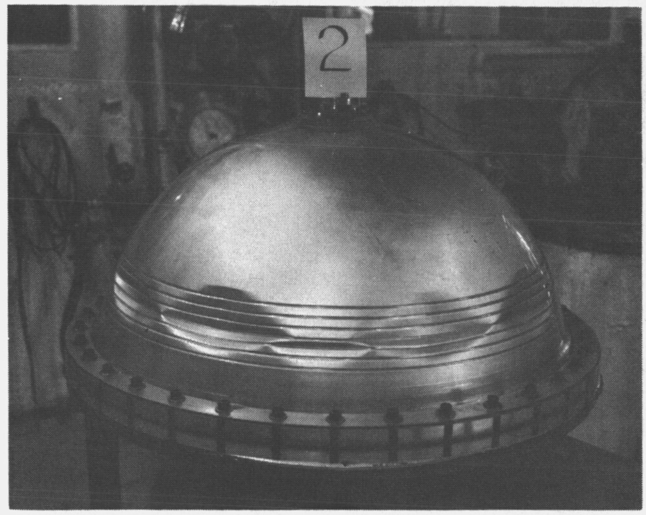


Figure 18B. Test Setup for Convoluted Diaphragm (Unit 8)



A



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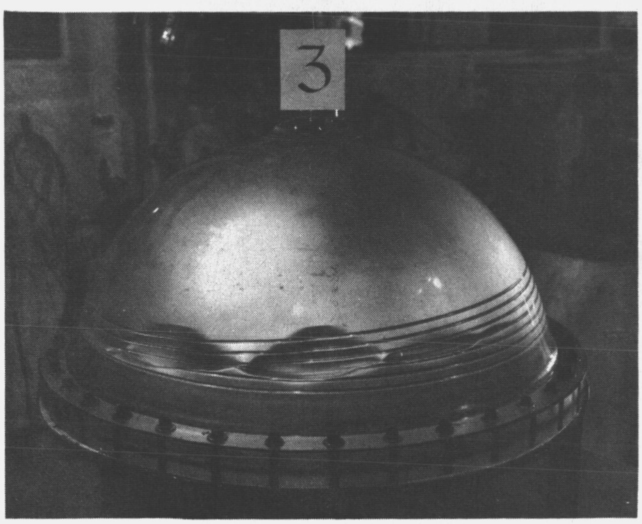

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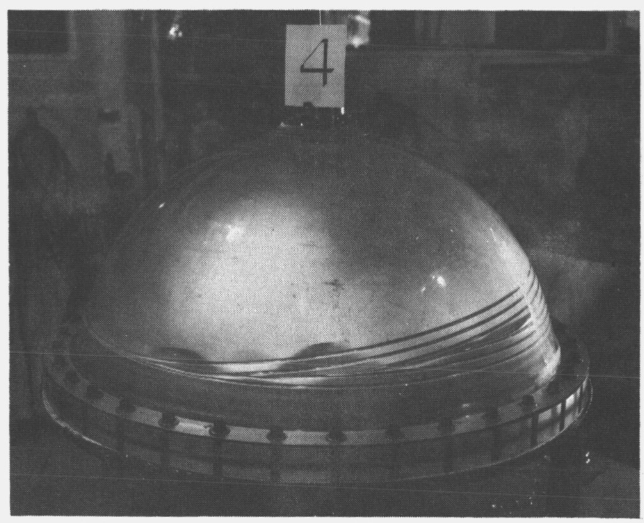
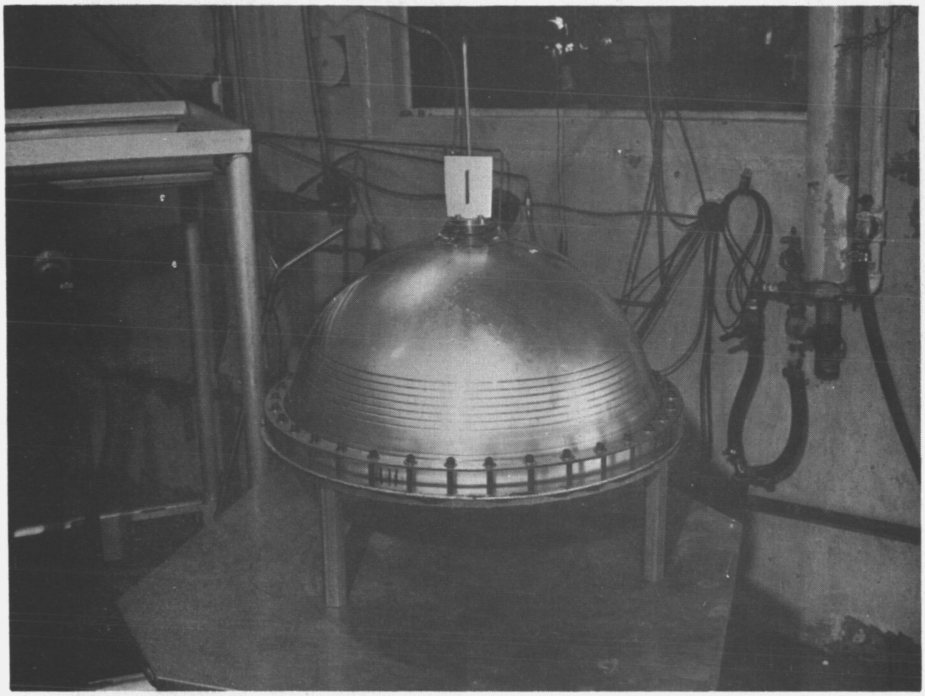


D

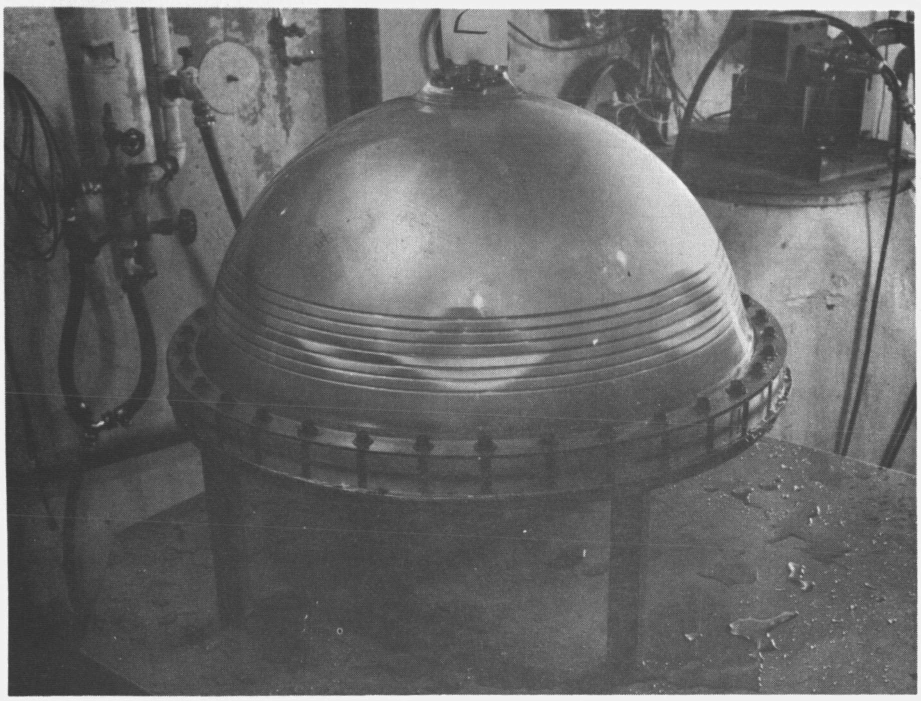
Figure 19. Performance Test, Unit No. 2

deformation at 13. 5 psig and a definite tendency to tip. A sizeable leak developed (Figure 19D) with 14 psig applied. The pressure was then increased to 40 psig in an attempt to further deflect the hemisphere; however, the area of the leak was too large to overcome with the available pressurant system and so the test was terminated.

Hemisphere No. 4 was the next unit tested. Figure 20 shows two steps of the initial portion of the test. Zero pressure was applied in step 1 (Figure 20A). Buckling began to occur in step 2, Figure 20B, at 12 psig. The test was interrupted at this point as it showed evidence of merely repeating the results of the first test. After removal of the hemisphere, an attempt was made to smooth out the buckles or dents. This was partially successful. The outermost reflected section of the hemisphere was then initially deflected a small amount by mounting the hemisphere on a milling machine face plate and rotating it while applying a slight pressure with a curved tool. The result of this method was not completely satisfactory since it produced a somewhat burnished surface finish and partially flattened the grooves. Figure 21 illustrates the results of continued tests on hemisphere No. 4. Figure 21A shows the unit readied for test with zero pressure applied. Figure 21 B shows severe buckling occurring at a pressure of 8 psig. In Figure 21C, with 11 psig applied, the outer and inner convolutions have completely reversed and there is evidence of another section beginning to deflect. The unit is fully collapsed in Figure 21D at 24 psig; however, close observation shows that two of the wide reinforcing bands have yielded and the final configuration deviates considerably from the normal convoluted configuration. Note that the reflected portion of the innermost convolution is lying almost flat against the test tank base plate. Following the action described for Figure 21D, the water pressure line was switched to a fitting at the bottom of the tank (labeled AIR OUT in the schematic Figure 18A. An attempt was then made to expel the diaphragm back out to the tank walls. Figure 21E, however, shows a large crack which developed at a pressure of 10 psig. This terminated tests on hemisphere No. 4.



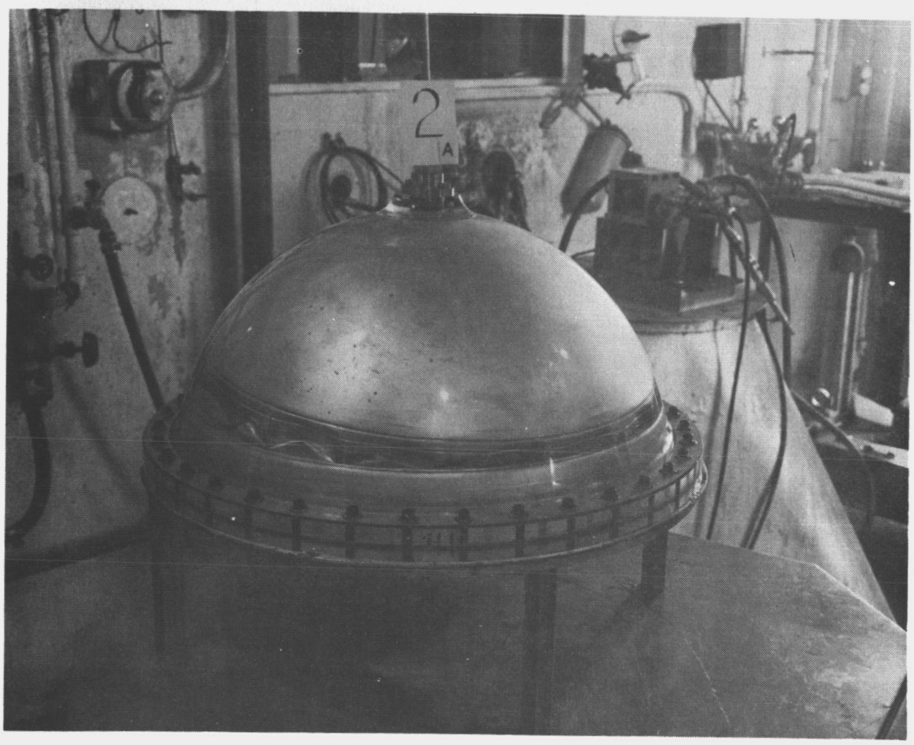
A



B

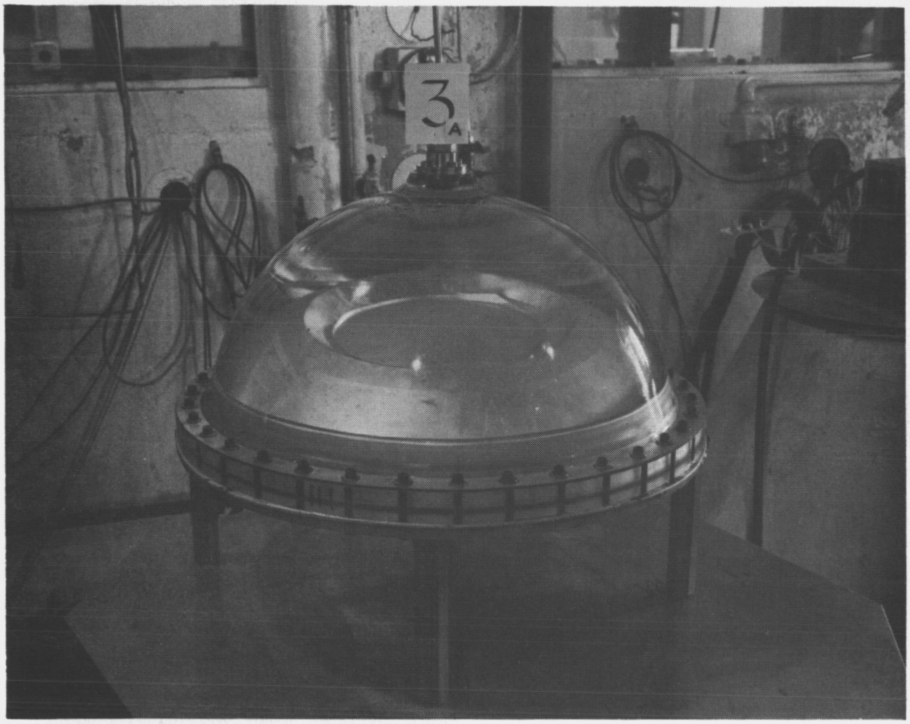
Figure 20. Performance Test, Unit No. 4

A

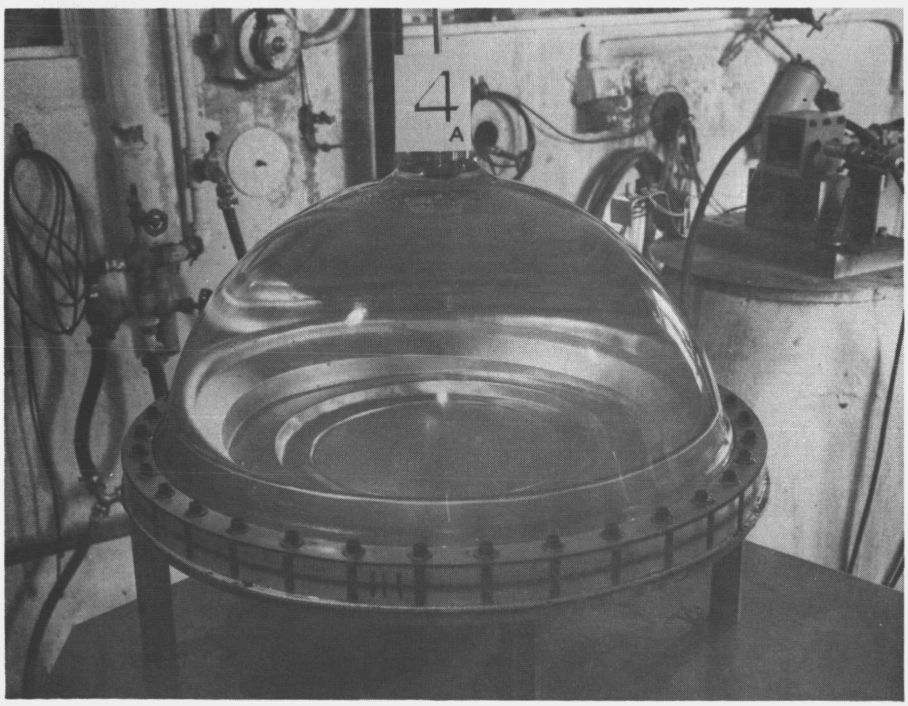


B

Figure 21. Performance Test, Unit No. 4, Run 2



C



D

Figure 21. Performance Test, Unit No. 4, Run 2

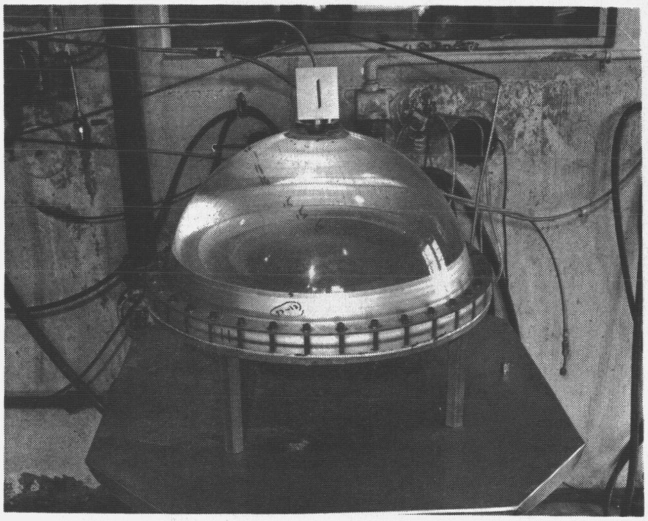
E

Figure 21. Performance Test, Unit No. 4, Run 2

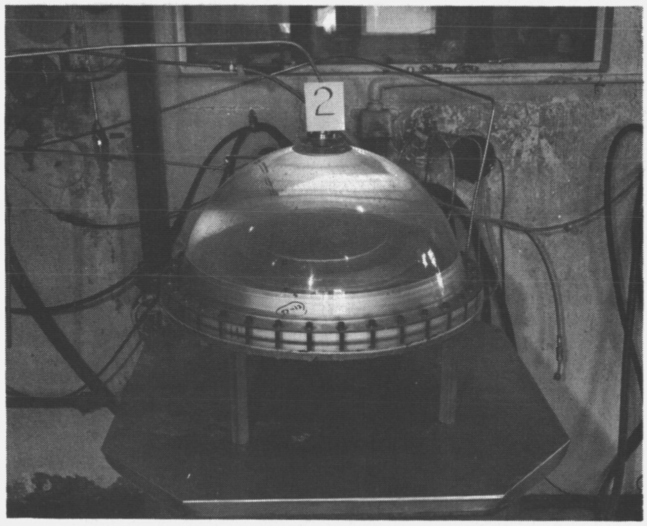
It was then decided to initially deflect the reflected sections of hemisphere No. 3 prior to testing. The hemisphere was mounted on the milling machine as was unit No. 4; however, instead of the stationary curved tool, a roller was made which had a nine inch curvature (same as hemisphere). As the roller came in contact with the rotating hemisphere, the roller also rotated and did not burnish the surfaces in contact. Although the finish was much improved, wrinkles appeared in the hemisphere as the metal was deflected and this method was abandoned. This unit was not tested. At this point it was decided that the remainder of the aluminum hemispheres should be convoluted with the telescopic punch and die. As was explained in the description of fabrication, only one of the remaining hemispheres convoluted successfully. This was unit No. 8 which had the chemically milled ribs. Figure 22 shows eight steps in sequence of the test conducted on this unit. Steps 1, 2, 3 and 4 (A, B, C and D) show the unit at 0, 5, 8 and 18 psi respectively during the expulsion half cycle. At 18 psi, step 4, all of the reflected sections had rolled out smoothly without any significant creases or folds. Note the absence of creases due to traveling folds which almost invariably appeared in previously tested units which did not have the hoop reinforcing in the outer convolution. Step 5 (Figure 22E) shows the unit at the start of the retraction half cycle with 4.5 psi applied above the diaphragm. Step 6 (Figure 22F) shows a later stage with 4.5 psi still applied. Note the tipping and random fold pattern. Step 7 (Figure 22G) shows the position of the diaphragm when it fractured as evidenced by water running out the bottom of the test fixture. At this point 8.5 psi was applied. Step 8 (Figure 22H) is actually the same as step 7 but with the diaphragm removed to more clearly show its condition. The crack is barely visible on the far side of the outer convolution.

CONCLUSIONS AND RECOMMENDATIONS

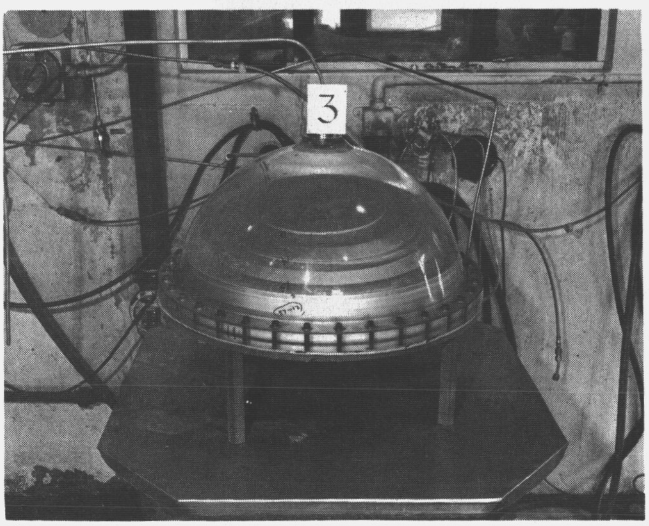
From the experience gained during both fabrication and test it is concluded that neither of the configurations of Figure 9 or 10 are desirable from a standpoint of increasing the performance of the all metal expulsion diaphragm. In fact,



A



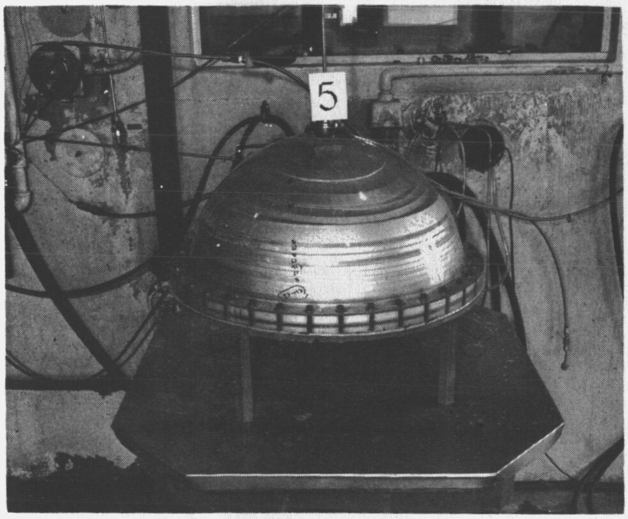
B



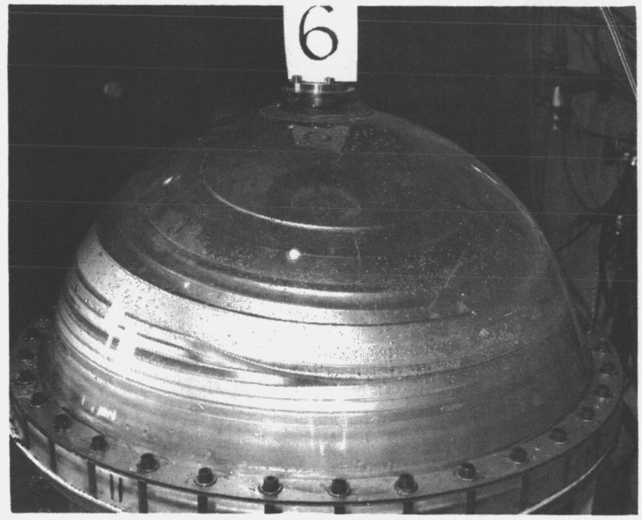
C

D

Figure 22. Performance Test, Unit No. 8



E



F

G

H

Figure 22. Performance Test, Unit No. 8

the performance is actually degraded from the performance of units which did not have the small reinforcing ribs but which only had the wide reinforcing bands in the "forward"sections as in phase III of the original contract. It appears that the added stress concentration provided by the stiffening ribs overshadows any advantage gained by the increase in hoop strength since cracking of the material occurs with considerably less severe buckles than had been observed in previous tests of units without the narrow ribs. It should be pointed out however, that both configurations required beginning with thick material which was chemically milled to obtain the thin sections. This proved to be difficult and, as pointed out in the description of fabrication, the resulting wall thickness tolerances were greater than desired. It is recognized that if closer tolerances could have been held, utilizing the same configurations, an improvement in the results of the foregoing tests may have been realized. This would require some means other than chemical milling to produce the desired cross section.

For further work in the area of reinforced diaphragms, the following recommendations are made:

1) Hold as close a tolerance on diaphragm wall thickness as possible.

2) Fabricate stiffening rings separately (with round cross section preferable for narrow hoop reinforcing rings).

3) Investigate methods of attaching rings to diaphragm such as electron-beam welding or brazing.

4) Try to avoid chemical milling, especially when more than a few mils thickness must be removed.

A close tolerance on diaphragm wall thickness is a very desirable feature since tipping and buckling are caused by the differences of thickness and/or stiffness between various points on the diagraphm wall.

Fabricating stiffening rings separality is advisable since it allows the hemisphere to be made from thin material to start with and does not require subsequent extensive chemical milling or machining. This permits much closer tolerances on wall thickness to be held. A ring with a round cross section is preferred for the narrow hoop reinforcing rings since it reduces the stress concentration by eliminating sharp edges.

Attachment of the rings to the diaphragm is a definite problem, however electron-beam welding and brazing appear to be two feasible methods which warrant investigation. Electron-beam welding is attractive from a performance standpoint since it would provide a strong bond with little more than line contact which would allow a maximum of flexibility of the diaphragm. Brazing would perhaps be more easily accomplished but would require at least a slight fillet between the ring and diaphragm which would reduce the flexibility. The type of material (eg. aluminum or stainless steel) may also be a determining factor in chosing the bonding method.

Chemical milling should be minimized or avoided completely, especially so in cases where more than a few mils of wall thickness must be removed. As proved in this program, holding a close thickness tolerance when chemical milling from a wall thickness of greater than 0.10 inch down to about 0.015 inch is very difficult if not impossible. An undesirable surface finish also results from chemical milling and becomes worse as the depth of mill increases. The most desirable diaphragms are formed from sheet stock of the same thickness as the desired end product (disregarding thinning during the forming process).

SECTION 4
PHASE VII

BACKGROUND

Since considerable success had been achieved in fabricating eighteen-inch aluminum expulsion diaphragms at Honeywell curiosity arose at both the Jet Propulsion Laboratory and Honeywell as to whether or not eighteen-inch diameter diaphragms could be made from other materials, namely; stainless steel and tetanium. Honeywell had already fabricated three-inch diameter stainless steel units. The reason for investigating other materials than aluminum stemmed from concerns about both propellant compatibility and diaphragm flexure or cycle life. It was on the basis of phase 9 of Honeywell Proposal Document 4-PH-694 that the Jet Propulsion Laboratory funded Honeywell to investigate the feasibility of fabricating eighteen-inch diameter expulsion diaphragms from stainless steel and titanium under modification 1 of JPL contract No. 950569.

DESIGN AND FABRICATION

From previous experience in fabricating three-inch diameter stainless steel diaphragms it was decided that 0.010 inch would be reasonable wall thickness for an eighteen-inch diameter stainless steel hemisphere. After comparing samples of stainless steel and titanium sheet stock, a wall thickness of 0.005 inch appeared desirable for the titanium. On the basis of ductility and formability, type 321 stainless steel and commercially pure titanium were chosen as the materials to use for this effort. Realizing the difficulty of forming these hemispheres it was decided to contact various metal forming companies which had displayed capabilities in this area. The following companies were contacted:

1) Super Metals Company - Santa Fe Springs, California
2) Jaycraft, Incorporated - El Cajon, California
3) Straza Corporation - El Cajon, California
4) Aircraft Hydroforming, Incorporated - Gardena, California
5) Jones Metal Company - West Lafayette, Ohio
6) Hydroforming of America - Chicago, Illinois

The first three companies were the first to be contacted. Although none of these three companies claimed any conclusive results from their experience at the time they were contacted, each felt confident that they could form the eighteen-inch diameter hemispheres from commercially pure titanium. All three companies had actual experience forming similar parts from type 321 stainless steel. After consideration of each company it was decided to submit a $ 500. 00 purchase order to Jaycraft, Incorporated to allow them to determine their ability at forming the titanium units. This order was submitted in lieu of a $6210. 00 order for ten eighteen-inch diameter titanium hemispheres quoted to Honeywell by Jaycraft on a "best effort" basis. Jaycraft proposed to use a proprietary process they called "Inturgescent Forming". After supposedly consuming the five hundred dollars plus funds of their own, Jaycraft terminated their effort without success. The main difficulty encountered, according to Mr. C. F. Lowum of Jaycraft, was cracking at the flange radius. About this time, Aircraft Hydroforming, Incorporated of Gardena, Claifornia was contacted. They had formed somewhat thicker titanium hemispheres in diameter larger than eighteen inches as witnessed by Mr. R. Michel, Honeywell Project Engineer, during a visit to their facility. Since neither Jones Metal Company or Hydroforming of America desired the challenge of fabricating the titanium hemispheres, a purchase order for five each of the stainless steel and titanium hemispheres was submitted to Aircraft Hydroforming, Inc. It was agreed that they would form the stainless steel units from 0. 010 inch thick stock and the titanium units from 0. 015 inch thick stock after which the titanium hemispheres would be chemically milled to 0. 005 inch thick. AHI would not reveal their forming process since it was developed "in house"

2

and is considered proprietary. According to Mr. Dean Warren of AHI, the process is a mixture of hydroforming and draw forming.

The stainless steel hemispheres were received at Honeywell approximately fourteen weeks after receipt of order, and the titanium units were received approximately six weeks later. A delivery of eight to twelve weeks ARO had been promised.

All hemispheres were smooth and wrinkle-free upon delivery. The outside diameter of the stainless steel units was almost exactly eighteen inches and fit the convoluting retaining ring extremely well. The diameter of the titanium units was about 0. 040 inch oversize. Thickness measurements taken at the flange of the hemispheres varied from 0. 0120 inch to 0. 0125 inch on the stainless steel units. The thinnest titanium units ran a constant 0. 005 inch while the thickest unit varied from 0. 008 to almost 0. 009 inch.

Since these units were 0. 020 to 0. 030 inch thinner than previously convoluted aluminum hemispheres and yet had about the same outside diameter or greater, a cut was made on the telescopic punch (while extended) to increase the effective radius. This left a slight gap between the hemisphere and punch down near the flange, but this was acceptable. The eopxy die portion of the convoluting tooling received a new molded face coat so that it would fit the new punch dimensions. Figures 23 and 23B show the first attempts at convoluting both the stainless steel and titanium.hemispheres. Note the wrinkles in the outer convolution of the stainless steel unit and the buckling occurring in the area of the outer convolution on the titanium part. From these results it was apparent that this area of the hemispheres needed some support during initial formation of the outer convolution. A removable epoxy ring was fabricated to provide this support. Figure 24 illustrates this ring in place in the telescopic punch. The hemispheres are convoluted down to point A after which the ring is removed and the convolution is completed. This ring proved to be the solution to the problem since the remaining four stainless steel hemispheres convoluted very satisfactorily as

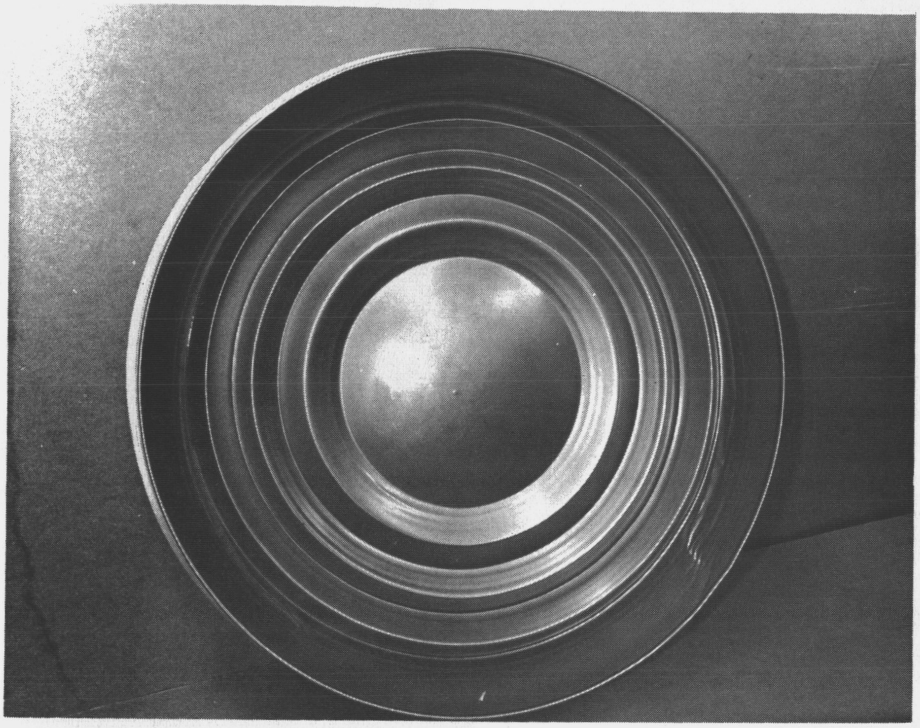


Figure 23A. Initial Convoluting Attempt -- Stainless Steel

Figure 23B. Initial Convoluting Attempt -- Titanium

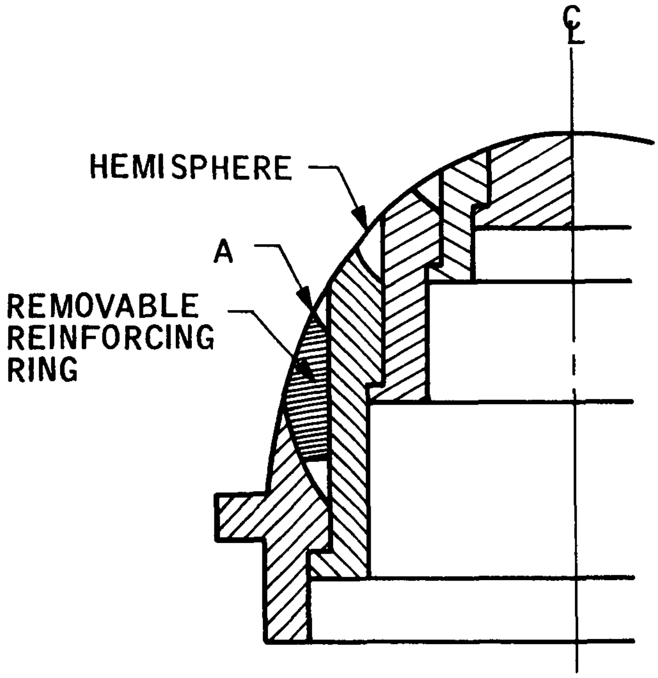


Figure 24. Telescope Punch with Removable Reinforcing Ring

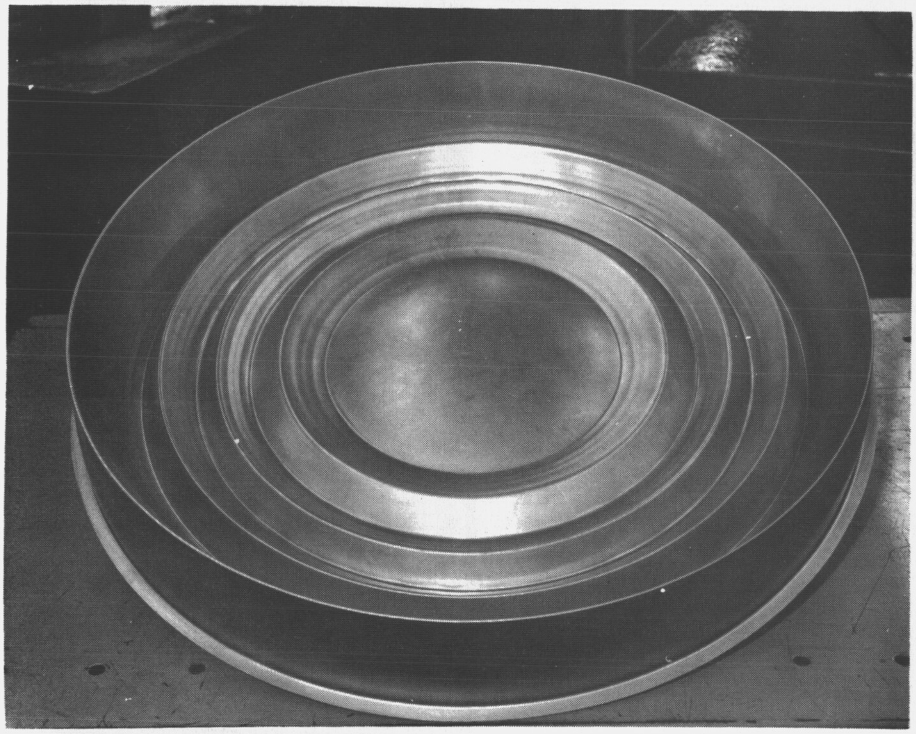


Figure 25A. Convoluted Stainless Steel Diaphragm -- 18 inch Diameter

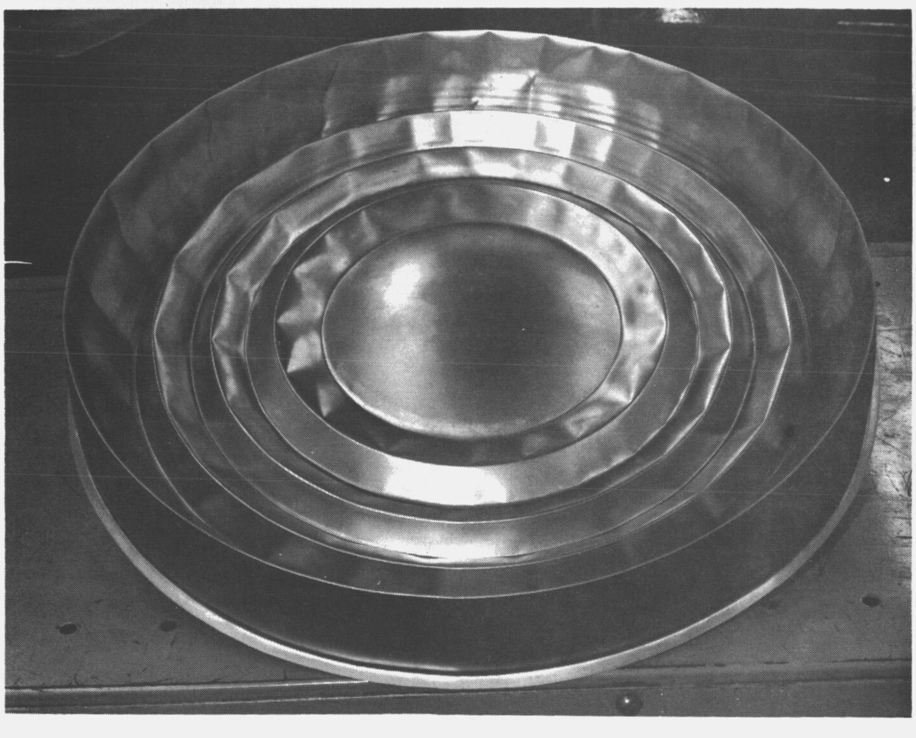


Figure 25B. Convoluted Titanium Diaphragm -- 18 inch Diameter shown in Figure 25A. The remaining four titanium units also convoluted quite satisfactorily. Springback of the titanium was expected, however no appreciable amount occurred. Although the reflected portions of the titanium units are wrinkled as evidenced by Figure 25B, no sharp creases occurred. The wrinkled appearance is believed due to some areas of the material yielding while some areas underwent the folding during convoluting without yielding. Some of the areas between the wrinkles show evidence of maintaining the original forward curvature although located in the reflected sections. This may or may not have occurred had the hemispheres been annealed prior to convoluting. Convoluting aluminum units in the past has been more successful without an anneal subsequent to the air-draw of the hemisphere therefore this experience was applied to the stainless steel and titanium units.

CONCLUSIONS AND RECOMMENDATIONS

From the results described, it is concluded that it is definitely feasible to fabricate eighteen inch diameter expulsion diaphragms from stainless steel and from titanium.

For future work in this area one might consider the following recommendations:

1) A wall thickness of 0.008 inch (nominal) should be tried for stainless steel diaphragms in the eighteen inch diameter range. The 0.012 inch thick material used in this program appears heavier and more rigid than necessary and/or desirable.

2) Experiments should be conducted in convoluting 0.005 inch thick titanium hemispheres which are in the annealed condition in an attempt to obtain a smoother contour.